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Surface soil responses to silage cropping intensity on a Typic Kanhapludult in the piedmont of North Carolina

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Abstract

Although reduced tillage itself is beneficial to soil quality and farm economics, the amount of crop residues returned to the soil will likely alter the success of a particular conservation tillage system within a farm operation. We investigated the impact of three cropping systems (a gradient in silage cropping intensity) on selected soil physical, chemical, and biological properties in the Piedmont of North Carolina, USA. Cropping systems were: (1) maize (*Zea mays* L.) silage/barley (*Hordeum vulgare* L.) silage (high silage intensity), (2) maize silage/winter cover crop (medium silage intensity), and (3) maize silage/barley grain—summer cover crop/winter cover crop (low silage intensity). There was an inverse relationship between silage intensity and the quantity of surface residue C and N contents. With time, soil bulk density at a depth of 0–3 cm became lower and total and particulate C and N fractions, and stability of macroaggregates became higher with lower silage intensity as a result of greater crop residue returned to soil. Soil bulk density at 0–3 cm depth was initially 0.88 Mg m^{-3} and increased to 1.08 Mg m^{-3} at the end of 7 years under high silage intensity. Total organic C at 0–20 cm depth was initially 11.7 g kg^{-1} and increased to 14.3 g kg^{-1} at the end of 7 years under low silage intensity. Stability of macroaggregates at 0–3 cm depth at the end of 7 years was 99% under low silage intensity, 96% under medium silage intensity, and 89% under high silage intensity. Soil microbial biomass C at 0–3 cm depth at the end of 7 years was greater with low silage intensity (1910 mg kg^{-1}) than with high silage intensity (1172 mg kg^{-1}). Less intensive silage cropping (i.e., greater quantities of crop residue returned to soil) had a multitude of positive effects on soil properties, even in continuous no-tillage crop production systems. An optimum balance between short-term economic returns and longer-term investments in improved soil quality for more sustainable production can be achieved in no-tillage silage cropping systems.
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Keywords: Aggregation; Bulk density; Conservation tillage; Organic carbon; Soil nitrogen; Soil quality

1. Introduction

Soil quality is a concept based on the premise that management can deteriorate, stabilize, or improve soil ecosystem functions. Soil provides a medium for plant growth, moderates and partitions water flow in the environment, and buffers the fluxes of natural and xenobiotic compounds through decomposition and fixation processes (Doran et al., 1994). The organic components of soil are important in providing energy, substrates, and the biological diversity necessary to sustain many soil functions.

Conservation tillage systems are now widely adopted by many producers, because they (Phillips et al., 1980; Hargrove, 1991; Langdale and Moldenhauer, 1995)

- reduce fuel, time, and labor needed to make multiple tillage operations,

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- reduce machinery wear,
- allow for more timely planting of crops even under wetter soil conditions,
- improve soil and water quality,
- reduce runoff and make more effective use of precipitation,
- improve wildlife habitat,
- meet farm bill requirements.

Although reduced tillage itself is beneficial to soil quality and farm economics, the amount of crop residues that is returned to the soil will likely alter the success of a particular conservation tillage system within a farm operation. Crop residues left at the soil surface as a surface mulch are important for feeding the soil biology, suppressing weed seed germination, and suppressing wide fluctuations in temperature and moisture that can hinder plant development. There is a need for more information on multiple-year impacts of different residue retention systems on surface soil properties in different environments.

The effect of increasing cropping intensity and associated increased crop residue production on soil C and N fractions has been investigated in several long-term experiments mostly in the Great Plains region of the USA and Canada. In the northern Great Plains, more intensive cropping systems with less bare fallow resulted (a) in greater particulate organic matter and soil microbial biomass C (Liebig et al., 2004), (b) in greater soil organic C, mineralizable C, and light fraction C (Janzen et al., 1998), and (c) in greater total and mineralizable C and N under both conventional and no tillage (Campbell et al., 1999). In the central Great Plains, more continuous cropping with less bare fallow also led to increases in particulate and total organic C (Peterson et al., 1998; Bowman et al., 1999). In southcentral Texas, increasing cropping intensity increased total, microbial biomass, and mineralizable C under both conventional and no tillage as a result of greater crop residue production (Franzluebbers et al., 1998).

In the humid region of the eastern USA, the impact of cropping intensity on soil C and N fractions has not been as frequently determined as in more arid regions. From the 'old rotation' cotton (*Gossypium hirsutum* L.) experiment in Alabama, including a legume cover crop nearly doubled soil organic C concentration compared with continuous cotton without a cover crop (Mitchell and Entry, 1998).

Dairy producers in North Carolina rely on maize (*Zea mays* L.) and barley (*Hordeum vulgare* L.) silage as sources of high quality feedstuffs in their rations. High-intensity silage cropping is typically practiced to maximize the amount of feedstuffs produced per unit of land area. High-intensity silage cropping, however, leaves little residue at the soil surface, offering little buffer against equipment traffic. The lack of residue returned to the soil under high-intensity silage cropping brings into question issues of low biological activity, long-term compaction, inefficient water use, poor nutrient cycling, and soil erosion.

Our objective was to determine the impact of alternative, reduced-silage-cropping-intensity systems that returned more crop residues to the soil than the traditional maize–barley silage cropping system on surface soil properties. We considered the soil surface a critical component of agroecosystems, because it is the vital interface that initially determines the fate of fertilizers, pesticides, water, and gases into and out of the soil profile.

2. Materials and methods

The site was located in Iredell County in the Southern Piedmont Major Land Resource Area of North Carolina, USA (36°N, 81°W). Soil was predominantly Fairview sandy clay loam (fine, kaolinitic, mesic Typic Kanhapludult) in Replication 1 and Braddock loam (fine, mixed, semiactive, mesic Typic Kanhapludult) in Replication 2. These soils were classified as well drained with moderate permeability. Long-term mean annual precipitation is 1220 mm and temperature is 14.4 °C.

Three cropping systems were replicated twice in ~300-m-long strips that were 12–20-m wide each. Plots were managed by the landowner with his field equipment. Replication 1 was established in 1998 and Replication 2 was established in 2000. All plots were managed with no tillage for several years prior to, as well as during experimentation. Previous management of the field with no tillage was without high residue input. Prior to no tillage, this field was managed with a 2–4-year rotational strip cropping system of perennial forage with maize silage. Total fertilizer and pesticide inputs and crop yields from 1999 to 2004 are described in Table 1.

The three cropping systems were designed as a gradient in silage intensity and inversely related to the amount of crop residues at the soil surface (Fig. 1). The traditional cropping system (high silage intensity) was maize planted in May and silage harvested in September followed by barley planted in November and silage harvested in April. This was a 1-year rotation and had the least above-ground residue returned to the soil. A medium silage intensity system was maize planted in May and silage harvested in September followed by a

Table 1
Total cumulative crop production inputs and outputs that occurred from this study from 1999 to 2004 as affected by silage cropping intensity in North Carolina

Crop production variable on a yearly basis	Silage cropping intensity		
	Low	Medium	High
Fertilizer inputs			
30% N (L ha^{-1})	1447 (6)	2073 (6)	2175 (6)
19-28-0-10 (kg ha^{-1})	202 (1)	202 (1)	202 (1)
17-17-24 (kg ha^{-1})	448 (2)	0 (0)	672 (3)
14-14-30 (kg ha^{-1})	0 (0)	0 (0)	336 (1)
12-24-24 (kg ha^{-1})	224 (1)	448 (2)	448 (2)
0-0-60 (kg ha^{-1})	146 (1)	146 (1)	560 (1)
Dairy slurry (2.6 N–2.5 P–7.8 K) (m^3 ha^{-1})	467 (3)	411 (3)	694 (4)
Pesticide inputs			
Accent (nicosulfuron) (mL ha^{-1})	25 (1)	50 (2)	50 (2)
Agrotrain (urease inhibitor) (L ha^{-1})	3.6 (1)	0.7 (1)	0 (0)
Ammonium sulfamate (L ha^{-1})	12.5 (3)	21.8 (5)	30.1 (5)
Atrazine (L ha^{-1})	5.5 (2)	9.5 (4)	13.4 (4)
Banvel (dicamba) (L ha^{-1})	0.7 (2)	0.8 (2)	0.7 (1)
Bicep (metolachlor) (L ha^{-1})	3.8 (1)	3.7 (1)	3.7 (1)
Bicep II (metolachlor) (L ha^{-1})	3.4 (1)	6.7 (2)	4.4 (1)
Exceed (prosulfuron/primisulfuron) (mL ha^{-1})	73 (1)	146 (2)	146 (2)
Force (tefluthrin) (kg ha^{-1})	13.4 (3)	22.4 (5)	22.2 (5)
Gramoxone (paraquat dichloride) (L ha^{-1})	16 (4)	19 (5)	12 (5)
Harmony (thifensulfuron methyl) (mL ha^{-1})	51 (2)	0 (0)	53 (2)
Hoelon (diclofop-methyl) (L ha^{-1})	2.4 (1)	0 (0)	2.4 (1)
Leadoff (dimethenamid) (L ha^{-1})	1.8 (1)	3.5 (1)	1.8 (1)
Princep (simazine) (L ha^{-1})	0.8 (1)	0.8 (1)	0.8 (1)
Roundup (glyphosate) (L ha^{-1})	6.8 (3)	8.0 (5)	13.8 (5)
Simagat (L ha^{-1})	4.8 (1)	4.6 (1)	4.6 (1)
Simazine (L ha^{-1})	2.6 (1)	5.8 (2)	5.8 (2)
Surfactant (L ha^{-1})	5.2 (5)	5.7 (5)	9.1 (5)
Harvested outputs			
Barley grain (Mg ha^{-1})	16.6 (3)	0 (0)	6.8 (1)
Cowpea grain (Mg ha^{-1})	2.9 (1)	0 (0)	0 (0)
Barley hay (Mg ha^{-1})	0 (0)	0 (0)	31.9 (3)
Barley silage (Mg_{wet} ha^{-1})	0 (0)	0 (0)	36.3 (2)
Maize silage (Mg_{wet} ha^{-1})	130.0 (3)	242.0 (6)	216.9 (6)

Not all inputs and outputs occurred each year, and therefore, values in parentheses indicate occurrence during the 6-year period. Total input or output divided by occurrence would result in the mean yearly value. Low silage intensity (0.5 crops $year^{-1}$); medium silage intensity (1 crop $year^{-1}$); high silage intensity (2 crops $year^{-1}$).

winter cover crop [rye (*Secale cereale* L.) alone or rye plus crimson clover (*Trifolium incarnatum* L.)] killed by a herbicide in April. This was a 1-year rotation and had a moderate level of crop residue returned. A low silage intensity system was maize planted in May and silage harvested in September followed by barley planted in November and grain harvested in June. Barley straw was left in the field and a summer cover crop [sudangrass (*Sorghum sudanense* Hitchc.), sunn-hemp (*Crotalaria juncea* L.), or cowpea (*Vigna unguiculata* (L.) Walp.)] planted in June and killed by frost in October. The summer cover crop was left in the field and followed by planting of rye as a winter cover crop in November, which was killed by a herbicide in April and residues left in the field. This was a 2-year rotation and had the highest level of crop residue returned. Expressed as silage cropping intensity, treatments had 0.5 (low silage intensity), 1 (medium silage intensity), and 2 (high silage intensity) silage crops harvested on a yearly basis.

Soil penetration resistance was determined at eight locations separated by 20 m within each plot in April and November 2004 with an impact penetrometer (Herrick and Jones, 2002). A 2-kg hammer was dropped 0.74-m distance repeatedly onto a 2-cm diameter cone with a 30° tip. The number of strikes required to reach a depth of 10, 20, and 30 cm was recorded. Each strike contained the equivalent kinetic energy of 14.5 J. Soil

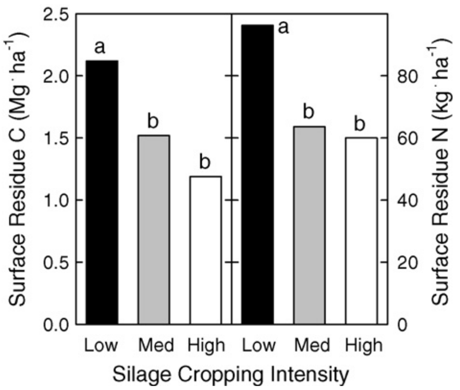

Fig. 1. Surface residue C and N content as affected by silage cropping intensity across four sampling events in North Carolina. Different letters above bars indicate difference among means at $p \leq 0.1$. Low silage intensity (0.5 crops $year^{-1}$); medium silage intensity (1 crop $year^{-1}$); high silage intensity (2 crops $year^{-1}$).

water content was determined at the same time at a depth of 0–20 cm with time-domain reflectrometry from the average of five measurements within a 2-m radius of each pentetrometer sampling.

Surface residue and soil were sampled in December 2000, February 2002, November 2002, April 2004, and November 2004. In December 2000, plots were sampled in duplicate by splitting the plot in half to assess within-plot variability, but means were used in subsequent evaluations. For each sample collected, eight sites located ca. 20 m apart were composited. Surface residue was collected from 20-cm × 20-cm areas by first removing green plant material above 4-cm height and then collecting all surface residue to ground level by cutting with a battery-powered hand shears. Following surface residue removal, a soil core (4-cm diameter) was sectioned into depths of 0–3, 3–6, 6–12, and 12–20 cm. Soil was dried at 55 °C for 3 days, initially passed through a sieve with openings of 4.75 mm to remove stones, a subsample ground in a ball mill for 5 min, and analyzed for total C and N with dry combustion. Soil bulk density was calculated from the total dry weight of soil and volume of coring device.

Dry aggregate distribution was determined by placing a 100-g subsample of soil on top of a nest of sieves (20-cm diameter with openings of 1.0, 0.25, and 0.05 mm), shaking for 1 min at level 6 on a CSC Scientific Sieve Shaker (catalogue no. 18480), and weighing soil retained on the 1.0, 0.25, and 0.05 mm screens and that passing the 0.05-mm screen (Kemper and Koch, 1966; Franzluebbers et al., 1999b). Water-stable aggregate distribution was determined from the same soil sample used for dry aggregate distribution placed on top of a nest of sieves (17.5-cm diameter with openings of 1.0 and 0.25 mm), immersed directly in water, and oscillated for 10 min (20-mm stroke length, 31 cycles min^{-1}). After removing the two sieves and placing them in an oven to dry, water containing soil passing the 0.25-mm sieve was poured over a 0.05-mm sieve, soil washed with a gentle stream of water, and the soil retained, transferred into a drying bottle with a small stream of water. The <0.05-mm fraction was calculated as the difference between initial soil weight and summation of the other fractions. All fractions were oven-dried at 55 °C for 3 days. Mean-weight diameter of both dry- and water-stable aggregates was calculated by summing the products of aggregate fractions and mean diameter of aggregate classes. Stability of mean-weight diameter was calculated as water-stable mean-weight diameter divided by dry-stable mean-weight diameter. Macroaggregates from both dry and wet sieving procedures were defined as ≥0.25 mm. Stability of macroaggregates was calculated as the fraction of water-stable macroaggregates divided by the fraction of dry-stable macroaggregates.

Particulate organic matter was isolated from soil by shaking 20–65-g subsamples of soil (inversely related to soil organic C concentration) in 100 mL of 0.01 M $Na_4P_2O_7$ for 16 h, passing the mixture over a sieve with 0.053-mm openings, and collecting the sand-sized material (Cambardella and Elliott, 1992; Franzluebbers et al., 1999b). Samples were dried at 55 °C for 24 h past visual dryness, weighed, ground to a fine powder in a ball mill, and analyzed for C and N concentration with dry combustion. Clay content from soil collected in December 2000 was determined prior to particulate organic matter determination in a 1-L cylinder with a hydrometer at the end of a 5-h settling period (Gee and Bauder, 1986).

Potential C mineralization was determined by placing two 20–65-g subsamples of soil in 60-mL glass jars, wetting to 50% water-filled pore space, and placing them in a 1-L canning jar along with 10 mL of 1 M NaOH to trap CO_2 and a vial of water to maintain humidity (Franzluebbers et al., 1999b). Samples were incubated at 25 ± 1 °C for up to 24 days. Alkali traps were replaced at 3 and 10 days of incubation and CO_2-C determined by titration with 1 M HCl in the presence of excess $BaCl_2$ to a phenolphthalein endpoint. At 10 days, one of the subsamples was removed from the incubation jar, fumigated with $CHCl_3$ under vacuum, vapors removed at 24 h, placed into a separate canning jar along with vials of alkali and water, and incubated at 25 °C for 10 days. Soil microbial biomass C was calculated as the quantity of CO_2-C evolved following fumigation divided by an efficiency factor of 0.41

(Voroney and Paul, 1984; Franzluebbers et al., 1999a). Potential N mineralization was determined from the difference in inorganic N concentration between 0 and 24 days of incubation. Inorganic N (NH_4-N + NO_2-N + NO_3-N) was determined from the filtered extract of a 10-g subsample of dried (55 °C for 48 h) and sieved (<2 mm) soil that was shaken with 20 mL of 2 M KCl for 30 min using salicylate-nitroprusside and Cd-reduction autoanalyzer techniques (Bundy and Meisinger, 1994). Mehlich-I extractable soil P was determined from the filtered extract of a 10-g subsample of dried (55 °C for 48 h) soil that was shaken with 40 mL of 0.05 M HCl + 0.0125 M H_2SO_4 for 15 min using a molybdate autoanalyzer technique (Olsen and Sommers, 1982).

Differences in mean soil properties across sampling events were evaluated with analysis of variance using SAS. Since the two replications in this experimental design were established 2 years apart, temporal changes in soil properties were evaluated through regression, rather than discrete sampling year effects. Sampling in December 2000 was after 3 and 1 years, in February 2002 was after 4 and 2 years, in November 2002 was after 5 and 3 years, in April 2004 was after 6 and 4 years, and in November 2004 was after 7 and 5 years (Replications 1 and 2, respectively). Stratification ratio of soil properties was calculated from the weighted concentration at a depth of 0–6 cm divided by the concentration at a depth of 12–20 cm (Franzluebbers, 2002). Differences among silage cropping intensity treatments were considered significant at $p \leq 0.1$.

3. Results

3.1. Soil physical properties

At initiation of this study, soil was characterized by lowest bulk density at 0–3 cm and highest density at 12–20 cm (Table 2). Macroaggregate stability and mean-weight diameter stability were generally uniformly distributed from 0 to 12 cm, but were lower at 12–20 cm. Lower stability of aggregates with depth reflected a difference in soil texture, in which clay concentration was 224 ± 23 mg g^{-1} at 0–12 cm and 282 ± 45 mg g^{-1} at 12–20 cm. With time, surface soil (0–3-cm depth) became more compacted with higher than with lower silage cropping intensity and became more stable in macroaggregates and mean-weight

Table 2
Soil physical properties within specific soil depths at the beginning (intercept) and with time (slope) as affected by silage intensity during 7 years of management in North Carolina

Soil depth (cm)	Intercept	Slope of silage cropping intensity (year^{-1})			CV	Contrasts (Pr > F)[a]	
		Low	Medium	High		L vs. M–H	M vs. H
Bulk density (Mg m^{-3})							
0–3	0.88	0.010	0.022	0.029*	12	0.13	0.60
3–6	1.33	−0.002	0.007	0.003	6	0.31	0.56
6–12	1.53	−0.009	−0.002	−0.016**	3	0.96	0.01
12–20	1.59	−0.019*	−0.012	−0.025*	5	0.98	0.16
0–20	1.43	−0.009	−0.001	−0.010	4	0.52	0.18
Macroaggregate stability ($g_{[wet]}\ g^{-1}_{[dry]}$)							
0–3	0.79	0.029***	0.024***	0.014*	6	0.03	0.07
3–6	0.79	0.011	0.020*	0.016*	7	0.25	0.64
6–12	0.82	0.005	0.004	0.003	4	0.55	0.87
12–20	0.66	0.028**	0.010	0.011	9	0.008	0.93
0–20	0.74	0.019***	0.011*	0.010*	5	0.04	0.77
Mean-weight diameter stability ($mm_{[wet]}\ mm^{-1}_{[dry]}$)							
0–3	0.62	0.042***	0.036**	0.021*	13	0.11	0.14
3–6	0.62	0.020*	0.031**	0.028*	13	0.25	0.76
6–12	0.66	0.009	0.014*	0.009	7	0.58	0.37
12–20	0.48	0.025**	0.009	0.006	15	0.02	0.69
0–20	0.57	0.021**	0.017*	0.013*	9	0.21	0.44

NS is not significant.
[a] L, low silage intensity (0.5 crops year^{-1}); M, medium silage intensity (1 crop year^{-1}); H, high silage intensity (2 crops year^{-1}).
* To the right of slope values indicate significance from zero at $p < 0.1$.
** To the right of slope values indicate significance from zero at $p < 0.01$.
*** To the right of slope values indicate significance from zero at $p < 0.001$.

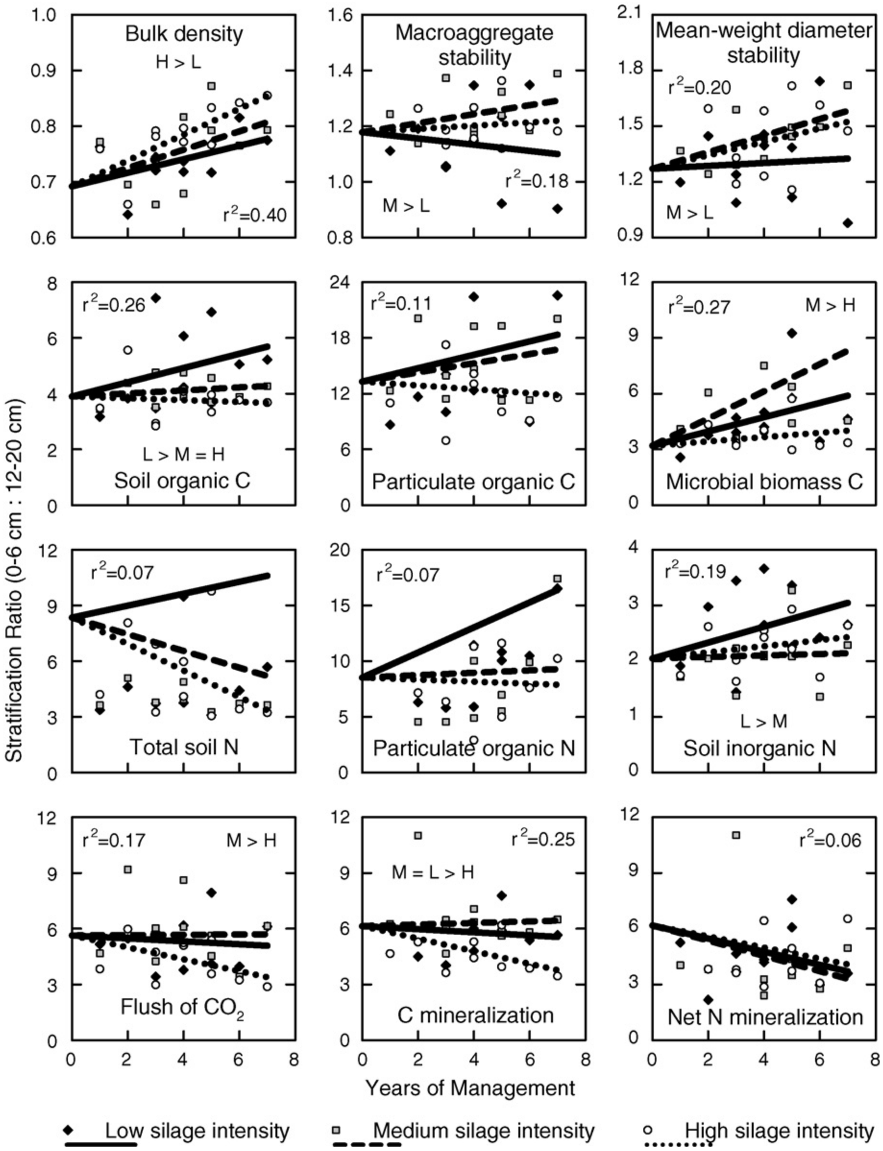

Fig. 2. Stratification ratio of various soil physical, chemical, and biological properties as affected by silage cropping intensity and years of management in North Carolina. Regressions were with a common intercept, assuming uniform conditions prior to management. Only those slope comparisons indicated in panel were significant at $p \leq 0.1$ (i.e. H > L, high greater than low silage intensity; L > M = H, low greater than medium and high silage intensity).

diameter with lower than with higher silage intensity (Table 2). Similar or non-significant changes occurred at lower depths with macroaggregate and mean-weight diameter stabilities, resulting in overall greater stabilities with time with lower than with higher silage intensity across the plow layer depth (i.e., 0–20 cm). Across the plow layer, bulk density was not affected by silage intensity or time.

Stratification ratio of soil bulk density increased with time under all silage cropping intensities, but more so under high than under low silage cropping intensity (Fig. 2). Soil bulk density can be considered a negative attribute, such that higher ratio indicates poorer surface soil condition. Results of stratification ratio of bulk density integrated the plow-layer changes that occurred and suggested that soil deteriorated more with high than with low silage intensity. Stratification ratio of macroaggregate stability and mean-weight diameter stability (Fig. 2) did not adequately reflect the positive surface soil conditions that occurred with low silage intensity, because of the concomitant positive changes that occurred at a depth of 12–20 cm (Table 1).

Table 3
Soil properties within specific soil depths averaged across sampling dates as affected by silage intensity in North Carolina

Soil depth (cm)	Silage Cropping Intensity			$L.S.D._{(p=0.1)}$
	Low	Medium	High	
Soil water content ($m^3\ m^{-3}$)[a]				
0–20	0.29	0.32	0.31	0.06
Penetration resistance (J)[a]				
0–10	66	82	88	10*
10–20	97	107	109	25
20–30	96	99	101	24
0–30	258	288	298	56
Carbon in large macroaggregates (1–4.75 mm) (mg g^{-1} aggregate)[b]				
0–3	58.9	51.9	55.3	16.0
3–6	24.7	23.3	22.5	3.5
6–12	12.3	12.2	13.1	2.1
12–20	7.6	7.7	8.5	1.3
0–20	16.4	15.6	16.6	1.6
Carbon in small macroaggregates (0.25–1 mm) (mg g^{-1} aggregate)[b]				
0–3	34.0	31.0	32.1	12.0
3–6	17.5	17.7	17.8	3.5
6–12	9.1	8.6	9.5	1.6
12–20	4.7	5.0	5.9	1.1
0–20	10.8	10.5	11.4	1.3
Carbon in microaggregates (0.05–0.25 mm) (mg g^{-1} aggregate)[b]				
0–3	28.1	24.4	29.9	7.5
3–6	16.7	16.3	17.8	1.7
6–12	9.4	8.4	9.6	1.5
12–20	5.7	5.4	6.2	1.4
0–20	10.6	9.8	11.4	0.9*

Low silage intensity (0.5 crops $year^{-1}$); medium silage intensity (1 crop $year^{-1}$); high silage intensity (2 crops $year^{-1}$).
[a] Sampled in April and November 2004.
[b] Sampled in February 2002 and April 2004.
* Indicates significant treatment difference.

Soil penetration resistance tended to be lower near the soil surface than deeper in the plow layer (Table 3). At a depth of 0–10 cm, penetration resistance was lower with low silage cropping intensity than with medium or high silage intensity. This was despite the slightly lower soil water content in this treatment that should have increased penetration resistance (Busscher et al., 1997). The greater accumulation of surface residue C with low silage intensity (Fig. 1) would likely have contributed to this loosening of surface soil. No difference in penetration resistance due to management occurred from 10 to 30-cm depth.

3.2. Soil chemical properties

At initiation of this study, soil contained highest concentration of all chemical properties measured at the surface and declining concentration with depth (Table 4). Initially stratified soil condition was due to previous no-tillage management at the site prior to establishment of the silage cropping treatments. With time, surface soil (0–3 and 3–6-cm depths) became either more enriched or less depleted in total and particulate organic C and N fractions with lower silage cropping intensity. The biggest change in C and N concentrations occurred with low compared with either medium or high silage intensity. Across the plow layer, a significant increase in total organic C and N occurred under low silage intensity. By including surface residue C with soil organic C to a depth of 20 cm, soil organic C sequestration followed the order: low silage intensity (0.55 Mg C ha^{-1} $year^{-1}$) > medium silage intensity (−0.20 Mg C ha^{-1} $year^{-1}$) < high silage intensity (0.33 Mg C ha^{-1} $year^{-1}$). Similar calculations for N were not significantly different among silage cropping intensities, but mean values were: 43 kg N ha^{-1} $year^{-1}$ under low silage intensity, −17 kg N ha^{-1} $year^{-1}$ under medium silage intensity, and 14 kg N ha^{-1} $year^{-1}$ under high silage intensity. Low silage intensity was able to contribute significantly to soil organic C

Table 4
Soil chemical properties within specific soil depths at the beginning (intercept) and with time (slope) as affected by silage intensity during 7 years of management in North Carolina

Soil depth (cm)	Intercept	Slope of silage cropping intensity ($year^{-1}$)			CV	Contrasts ($Pr > F$)[a]	
		Low	Medium	High		L vs. M–H	M vs. H
Soil organic C ($mg\ g^{-1}$)							
0–3	35.3	1.52	−0.17	−0.17	21	0.02	0.99
3–6	17.8	0.98	−0.08	0.20	25	0.04	0.58
6–12	10.0	0.06	−0.09	0.24	12	0.87	0.01
12–20	6.4	−0.05	−0.11	0.07	13	0.73	0.04
0–20	11.7	0.37*	−0.01	0.25	10	0.03	0.05
Particulate organic C ($mg\ g^{-1}$)							
0–3	21.5	0.20	−0.91	−0.85	27	0.03	0.90
3–6	7.6	0.39*	−0.38*	−0.11	57	<0.001	0.15
6–12	3.2	−0.09	−0.25*	−0.07	33	0.38	0.05
12–20	1.0	−0.00	−0.07*	−0.01	24	0.10	0.01
0–20	4.5	0.09	−0.21**	−0.05	15	<0.001	0.02
Total N ($mg\ g^{-1}$)							
0–3	3.57	0.108	−0.076	−0.107	23	0.01	0.71
3–6	1.82	0.084	−0.047	−0.020	35	0.05	0.69
6–12	0.89	0.006	−0.002	0.012	23	0.97	0.51
12–20	0.46	0.011	0.007	0.021	44	0.86	0.55
0–20	1.07	0.036*	−0.004	0.011	16	0.05	0.42
Particulate organic N ($mg\ g^{-1}$)							
0–3	1.35	0.032	−0.056	−0.046	26	0.01	0.77
3–6	0.47	0.045*	−0.014	−0.006	32	<0.001	0.61
6–12	0.21	0.000	−0.005	0.002	56	0.90	0.55
12–20	0.09	0.001	−0.000	0.001	76	0.95	0.84
0–20	0.30	0.013	−0.007	0.000	31	0.08	0.49
Inorganic N ($\mu g\ g^{-1}$)							
0–3	47	−3.3*	−5.1***	−4.8**	38	0.11	0.75
3–6	39	−3.9**	−4.9***	−4.5**	50	0.40	0.69
6–12	31	−4.0***	−4.3***	−3.5**	55	0.91	0.37
12–20	22	−2.7**	−2.8**	−2.7**	56	0.90	0.90
0–20	30	−3.3***	−3.8***	−3.4***	48	0.71	0.62
Extractable P ($\mu g\ g^{-1}$)							
0–3	111	−6.1	−7.6*	−10.2*	41	0.86	0.23
3–6	63	1.8	−4.8	−3.0	52	0.11	0.12
6–12	22	1.1	−1.8*	−0.6	33	0.002	0.02
12–20	4	0.4	−0.3	0.0	50	0.006	0.11
0–20	28	0.3	−2.0*	−1.4*	28	0.02	0.02

NS is not significant.
[a] L, low silage intensity (0.5 crops $year^{-1}$); M, medium silage intensity (1 crop $year^{-1}$); H, high silage intensity (2 crops $year^{-1}$).
* To the right of slope values indicate significance from zero at $p < 0.1$.
** To the right of slope values indicate significance from zero at $p < 0.01$.
*** To the right of slope values indicate significance from zero at $p < 0.001$.

sequestration and accumulation of N, both characteristics of improved soil quality.

Soil inorganic N declined with time under all management systems and at all soil depths (Table 4). Extractable soil P tended to decline with medium and high silage intensity, although never significantly with low silage intensity. During the study period, there was a shift in fertilizer application strategy away from inorganic sources to organic application with dairy manure slurry, which may have contributed to the decline in soil inorganic N with time. Increasing maize silage frequency appeared to have reduced P concentration in soil.

Carbon concentration in soil was greater in large macroaggregates than in small macroaggregates or microaggregates (Table 3). Like that of whole soil, C concentration in all aggregate fractions decreased with depth. There were no differences in C concentration among silage cropping intensities in any of the aggregate fractions, except in microaggregates when averaged across depths. For an unknown reason, C concentration in microaggregates was lower under medium than high silage cropping intensity. The C:N ratio of aggregate fractions was 12.3 ± 1.0. Responses of N concentration in aggregate fractions were similar to those of C with respect to depth, aggregate size, and silage intensity.

Stratification ratio of soil organic C and inorganic N increased with time under low silage cropping intensity, but was stable with time under medium and high silage intensity (Fig. 2). Trends were similar for total N and particulate organic C and N, but effects were not significant due to higher variability. Increasing stratification of soil organic matter pools with greater crop residue input (i.e., lower silage intensity) reflected the large and immediate impact that surface residue accumulation (Fig. 1) can have on surface soil properties.

3.3. Soil biological properties

As with soil chemical properties at the initiation of this study, soil contained highest concentration of all biological properties measured at the surface and declining concentration with depth (Table 5). Changes in soil biological properties with time were rarely

Table 5
Soil biological properties within specific soil depths at the beginning (intercept) and with time (slope) as affected by silage intensity during 7 years of management in North Carolina

Soil depth (cm)	Intercept	Slope of silage cropping intensity ($year^{-1}$)			CV	Contrasts (Pr > F)[a]	
		Low	Medium	High		L vs. M–H	M vs. H
Soil microbial biomass C ($\mu g\ g^{-1}$)							
0–3	1824	12.3	−56.4	−93.2	30	0.06	0.47
3–6	864	2.0	−23.6	−16.9	21	0.15	0.70
6–12	527	−12.4	−16.6	−6.6	18	0.92	0.27
12–20	338	−14.6*	−27.1***	−12.0	22	0.36	0.02
0–20	607	−5.4	−22.1*	−13.7	15	0.10	0.32
Flush of CO_2 following rewetting of dried soil ($\mu g\ CO_2$–C g^{-1} 3 $days^{-1}$)							
0–3	607	−11.6	−9.6	−32.3	31	0.53	0.20
3–6	318	−4.3	−8.5	−13.0	26	0.34	0.56
6–12	169	−5.0	−5.0	−2.6	18	0.63	0.42
12–20	77	−0.7	−0.9	2.0	25	0.94	0.17
0–20	188	−1.9	−2.7	−3.0	19	0.76	0.92
Potential C mineralization ($\mu g\ CO_2$–C g^{-1} 24 $days^{-1}$)							
0–3	1732	−16.7	−43.8	−95.6	34	0.26	0.33
3–6	856	−15.7	−22.0	−26.1	31	0.70	0.87
6–12	440	−7.1	−17.7*	−5.8	18	0.47	0.12
12–20	198	1.0	−6.4	4.4	26	0.66	0.05
0–20	507	−2.2	−11.9	−7.4	22	0.44	0.68
Net N mineralization [$\mu g\ (NO_3 + NH_4)$–N g^{-1} 24 $days^{-1}$]							
0–3	110	2.7	−0.8	−2.5	33	0.19	0.65
3–6	85	−3.4	−6.3*	−1.7	42	0.82	0.14
6–12	42	−1.2	−0.7	−0.4	37	0.58	0.84
12–20	21	0.2	−0.5	−0.2	34	0.38	0.68
0–20	45	−0.4	−1.2	−0.3	25	0.67	0.44
Net nitrification [g NO_3–N g^{-1} N mineralized]							
0–3	0.94	−0.010	−0.003	−0.001	17	0.57	0.88
3–6	0.86	0.002	0.007	0.003	28	0.89	0.85
6–12	0.87	−0.003	0.001	−0.002	35	0.92	0.94
12–20	0.69	0.029	0.029	0.031	60	0.98	0.97
0–20	0.79	0.011	0.014	0.014	39	0.92	0.99

NS is not significant.

[a] L, low silage intensity (0.5 crops $year^{-1}$); M, medium silage intensity (1 crop $year^{-1}$); H, high silage intensity (2 crops $year^{-1}$).

* To the right of slope values indicate significance from zero at $p < 0.1$.

*** To the right of slope values indicate significance from zero at $p < 0.001$.

significant, except in medium silage cropping intensity, which had reductions in soil microbial biomass C and potential C and N mineralization at one of the four depths measured. Soil microbial biomass C at a depth of 0–3 and 0–20 cm was maintained at a higher level with time under low than medium or high silage intensity. Although not significant, a similar gradient of maintaining higher potential C and N mineralization with lower than higher silage intensity occurred at the soil surface.

Stratification ratio of soil microbial biomass C, potential C mineralization, and the flush of CO_2 following rewetting of dried soil became greater with time under medium than high silage cropping intensity (Fig. 2). Stratification ratio effects reinforced the significant changes in surface soil microbial biomass C and more effectively highlighted the trends in potential C mineralization and the flush of CO_2 following rewetting of dried soil.

Net N mineralization tended to decline with time at all soil depths (Table 5) and as a stratification ratio (Fig. 2). Declining N mineralization with time was a reflection of declining C mineralization and soil microbial biomass C. The flush of CO_2 following rewetting of dried soil was highly predictive of net N mineralization (Fig. 3). Longer term C mineralization and soil microbial biomass C were also highly related to the flush of CO_2 following rewetting of dried soil.

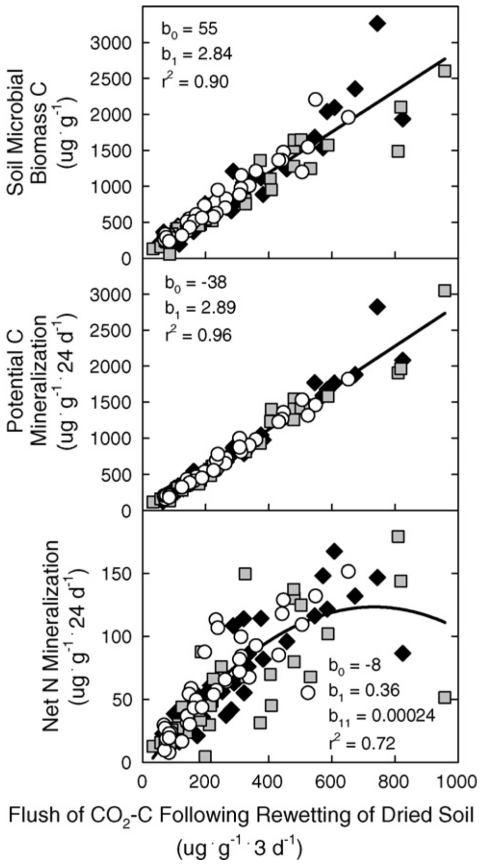

Fig. 3. Relationship of the flush of CO_2 following rewetting of dried soil to soil microbial biomass C, potential C mineralization, and net N mineralization. (◆) Is low silage intensity, (■) is medium silage intensity, and (○) is high silage intensity.

4. Discussion

This study suggests that compaction was occurring at a steady rate with high silage cropping intensity, but that compaction could be alleviated by low silage intensity with high surface residue return. The slow conversion of organic matter from crop residues into soil organic C, especially at the soil surface, can lead to a large reduction in soil bulk density (Franzluebbers et al., 2001). Organic matter has a much lower specific density than mineral soil and the incorporation of organic matter as a result of soil faunal and microbial activity often leads to a more porous soil matrix. Soil biological activity is also important for fabricating water-stable aggregates.

Total, particulate, microbial biomass, and mineralizable C and N fractions and extractable soil P were highly stratified with depth under all management systems in this study as a result of long-term management with conservation tillage. A greater degree of stratification with time generally only took place with high crop residue input (i.e., low silage intensity). Return of organic substrates to the soil surface is necessary to maintain high surface soil biological activity, which fosters water and nutrient efficiency and prevents soil compaction. Stratification of soil P is common in no-tillage management systems (Triplett and Van Doren, 1969; Bauer et al., 2002), and distribution does not appear to affect crop uptake potential (Singh et al., 1966).

The degree of stratification of various soil organic matter fractions can be used as an indicator of soil quality or soil ecosystem functioning, because surface organic matter is essential to erosion control, water infiltration, and conservation of nutrients (Franzluebbers, 2002). Increased stratification is likely to (1) improve water efficiency by reducing runoff and increasing retention in soil, (2) improve nutrient cycling by slowing mineralization and immobilizing nutrients in organic fractions rather than losing them in runoff and leachate, (3) resist degradative forces of wind and water erosion and mechanical compaction, (4) improve soil biological diversity, and (5) enhance long-term productivity of soils. With no-tillage management of a silt loam in Ohio, water runoff and soil loss were reduced linearly with increasing percent of soil covered by maize residue (Triplett et al., 1968). This same effect was also observed at the end of 18 years of no-tillage management (Van Doren et al., 1984).

Noteworthy in this study, was the effect of higher total C and N in soil in response to reduced silage cropping intensity on the per-crop maize silage yield. Across 6 years of evaluation, maize silage yield was lower with low than with high silage intensity on a yearly basis (Table 1), but was greater with low than with high silage intensity per crop harvested (i.e., 21.7 Mg $ha^{-1} \times 2$ years = 43.4 Mg ha^{-1} $year^{-1}$ versus 36.2 Mg ha^{-1} $year^{-1}$). A large part of this effect was due to yield during 2004, when liquid manure was not applied due to weather/labor complications. The accumulation of total soil N with low silage intensity and the decline of total soil N with high silage intensity (Table 4) allowed more N to be available to the maize crop with low silage intensity in 2004, when N application was lower than normal. Soil N availability in these cropping systems tended to be sufficient in other years, since small-plot tests in 2002 and 2003 with 56 and 112 kg N ha^{-1} reductions in N application produced equivalent yield to the normal N application rate (data not shown).

Although soil microbial biomass represented only ≈5% of the soil organic C, it plays a major role in organic matter decomposition and nutrient cycling. Changes in soil microbial biomass may be an early indicator of long-term changes in soil organic matter (Powlson et al., 1987). Soil microbial biomass is also an important mediator in the biophysical manipulation of soil structure. The positive change in macroaggregation of surface soil with increasing crop residue input (i.e., lower silage intensity) was consistent with the positive changes in total, particulate, and microbial C and N fractions.

Relating net N mineralization to potential C mineralization during 24 days of incubation resulted in a C:N ratio of 10.9 with a coefficient of determination of 0.61 (data not shown). The relatively high C:N ratio indicated that N availability in soil would be largely influenced by C cycling dynamics. The curvilinear relationship between net N mineralization and the flush of CO_2 suggests a threshold level of microbial activity at about 600 μg CO_2-C g^{-1} 3 $days^{-1}$ (Fig. 3), below which N cycling would be dominated by net N mineralization and above which N cycling would be dominated by net N immobilization. A similar relationship between net N mineralization and the flush of CO_2 following rewetting of dried soil was observed in soils from Alberta, British Columbia, Maine, Texas, and Georgia (Franzluebbers et al., 2000). They suggested that the flush of CO_2 would be an ideal biological soil testing protocol, because of simplicity, convenience, and strength of relationships with other biological soil quality indicators. Our data confirmed that the procedure is simple, rapid, and reliable, and highly related to other more traditional biochemical indicators.

5. Conclusions

Soil physical, chemical, and biological properties such as bulk density, macroaggregate stability, and total, particulate, and microbial C and N fractions responded positively to greater crop residue input with lower silage cropping intensity, leading to an improvement in soil quality. Soil organic C and N fractions were highly stratified with depth under all management systems in this study as a result of long-term management with conservation tillage. Return of organic substrates to the soil surface was necessary to further increase high surface soil biological activity, which would foster water and nutrient efficiency and prevent soil compaction. Sufficient quantity of residue returned to the soil is necessary for organic matter transformations to facilitate the development of an improved soil condition.

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